RADIO NAVIGATION OF DEEP SPACE 1 DURING ION PROPULSION USAGE

Timothy P. McELRATH, Dongsuk HAN, & Mark S. RYNE

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

ABSTRACT - One of the main goals of the Deep Space 1 (DS1) project was to demonstrate the use of ion propulsion on an interplanetary spacecraft. The navigation of a low-thrust spacecraft presents unique challenges both in general, and as part of a technology demonstration effort. A theoretical analysis of range and Doppler tracking of a spacecraft under continuous low thrust finds that geocentric declination knowledge is seriously degraded, especially for short (6 hours or less) passes, and this result is validated numerically. The DS1 Ion Propulsion System (IPS) performance was measured using Doppler and range tracking data at the beginning and end of the prime mission, and found to be within an acceptable range of values, although generally lower than the nominal thrust levels by about 1 to 2 percent. Radio navigation performance metrics during an extended period of IPS operation show that the operational mode used by DS1 was adequate for meeting mission navigational requirements, which include providing a reference against which to measure the autonomous onboard optical navigation.

1 - INTRODUCTION

1.1 - Mission Description

The DS1 mission is the first in a series of technology validation missions designed to enable and/or lower the cost of future science missions. The demonstration of solar electric propulsion was the highest priority goal of the mission, with autonomous navigation being one of several goals at the next level of importance. The total list of technologies and a more complete mission description are given in [Rayman 99]. In addition to technology goals, and somewhat in support of them, the spacecraft trajectory was designed to encounter the asteroid Braille (formerly 1992 KD) within nine months after launch, with encounters of another asteroid and a comet included afterwards during the extended mission phase.

In pursuit of the technology validation goals, the mission plan included an intense period of testing beginning a few days after launch, at a time where the operations teams of most science missions are still becoming familiar with their spacecraft. The IPS had a series of tests before the first attempt to develop and calibrate the design thrust 17 days after launch, which occurred on October 24, 1998. In addition, the optimum trajectory included about a month of thrusting during the first two months after launch, allowing the spacecraft team to develop experience with IPS usage. The autonomous onboard navigation system (Autonav), described by [Riedel 97] and [Bhaskaran 98], tested many of its functions during the first two months, taking advantage of the high telecommunications bandwidths typical of a near-Earth mission phase by returning many calibration and test images.

1.1 - Spacecraft Description

The DS1 spacecraft design consists of a roughly cylindrical bus with two large gimbaled solar panels extending from each side (along the spacecraft Y axis). The IPS is attached to the -Z side of the spacecraft bus, with the camera and star tracker fields-of-view on the opposite side of the IPS. In addition to the IPS, the DS1 spacecraft includes a monopropellant hydrazine Reaction Control System (RCS) for attitude control, consisting of eight 1-Newton thrusters. All of these are mounted close to the IPS, with four thrusting in the spacecraft +Z direction (the same direction as IPS thrust), and two each in the spacecraft +X and -X directions. Since navigation with radio tracking depends on accurate spacecraft non-gravitational force modelling, it is important to note that the Z-facing thrusters (used for X- and sometimes Y-axis attitude control) operate in a completely unbalanced mode, while the X-facing thrusters have a balanced mode for Z-axis control, and a semi-balanced mode for Y-axis control. The X thrusters are always used for turns about the Y-axis, since they have a much larger moment arm, but the Z thrusters are used when finer Y-axis control is needed. Since there are no momentum wheels on the spacecraft, all attitude control is based on deadbands, although the IPS (when running) provides attitude control in the spacecraft X- and Y-axes through continuous gimballing. The lack of either balanced thrusters or momentum wheels in the DS1 attitude control system configuration will be seen to contribute significant challenges to all phases of radio navigation described below.

2 - THEORETICAL CONSIDERATIONS

2.1 - Analytic Results

Radio tracking data that consists of range and Doppler from a single station have been shown to provide the geocentric range, range-rate, right ascension, and declination of the spacecraft in a single tracking pass, due to the station's motion caused by the rotation of the Earth. Analytical estimates of the accuracy of the derived angular measurements originally neglected the effect of geocentric acceleration uncertainty, since the first several generations of spacecraft had fairly low non-gravitational errors compared to the tracking data accuracy. This analysis was extended by [McElrath 95] to include acceleration uncertainty for Doppler data, in addition to looking for any changes necessitated by the then-unique high declinations experienced in tracking Ulysses in 1994-5. The conclusion of this study was that a significant loss of declination information is a result of high levels of geocentric acceleration uncertainty.

This result is relevant to DS1 both as a low-thrust mission and as a spacecraft with a high level of unbalanced attitude control acceleration. The maximum thrust of the IPS (coincident with the maximum power available on the mission trajectory) is is about 78 milli-Newtons (mN), producing an acceleration of 1.6×10^{-7} km/sec^2 for the 486 kg launch mass of DS1. The pre-flight IPS thrust uncertainty was expected to be up to 2 percent, and even 0.1 percent is still larger than the 10^{-10} km/sec^2 acceleration uncertainties considered in [McElrath 95] for Ulysses. Even without IPS operation, the DS1 Z-facing thrusters produce an average acceleration of up to 4×10^{-10} km/sec^2, with short-term variations at 10 percent of that level. While balanced thrusters, reaction wheels, spinning spacecraft, or inertial estimates of spacecraft delta-V can reduce this effect for coasting spacecraft, any useful low-thrust spacecraft will have navigationally significant acceleration errors, based on DS1 IPS experience.

The analysis outlined in [McElrath 95] was extended to include range data for this paper. The information array for range observation partials (which are just the integral of the Doppler partials) can be accumulated analytically, with many of the same forms as for Doppler observations, and the combined range and Doppler information array maintains the same sparseness due to symmetry considerations. However, while analytic inversion would be possible, the resulting equations appear to be too complicated to contribute significantly to insight into the problem. Consequently, the information array was evaluated and inverted numerically. The resulting angular uncertainties as a function of pass length and acceleration are shown for a declination of 10 degrees in Figure 1. Due the symmetry in the problem, acceleration uncertainty does not effect right ascension, which is therefore purely a function of pass length. It turns out that a 1 meter range weight is roughly equivalent to 1 mm/sec Doppler for angular information content, but the 0.1 mm/sec X-band Doppler that is routinely available from the NASA/JPL Deep Space Network (DSN) is much more effective than 1 meter ranging. It is important to note that 4 to 6 hour passes produce a relatively ineffective measure of angular position in at least one component, and a factor of 2 or more improvement are typical for 2 hour pass length extensions starting from 6 hours duration.

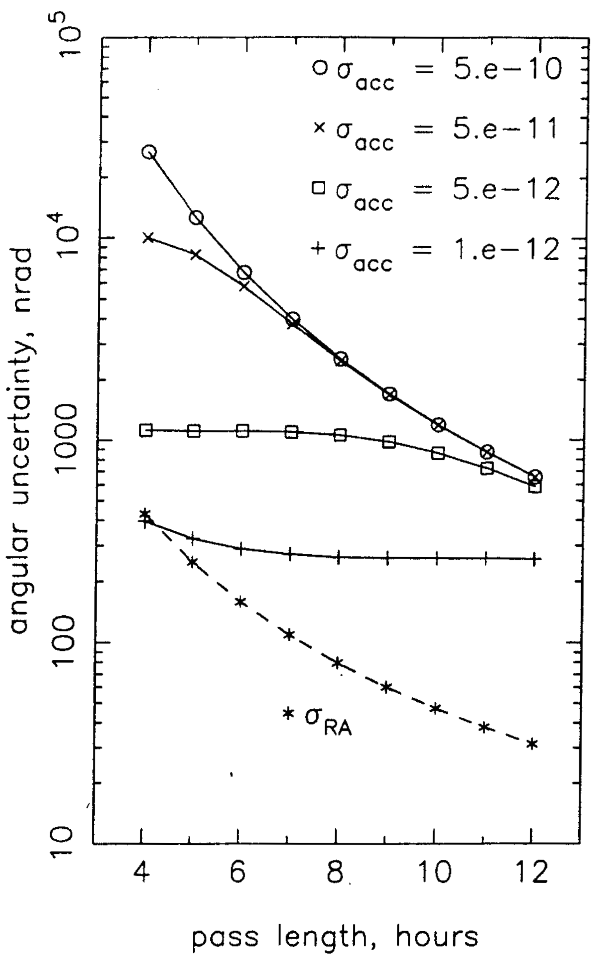

Fig. 1: Geocentric angular uncertainties as a function of acceleration uncertainty and pass length. Declination values are connected by solid lines, and right ascension values by a dashed line. For 0.01 mm/sec Doppler every minute and 1.0 m range every five minutes.

2.2 - Numerical Results

Clearly large acceleration errors have a significant effect on the declination uncertainty for a single tracking pass. However, two consecutive passes would be expected to reduce the correlation between declination and acceleration such that a better angular estimate is obtained. Simple analytic results, based on taking the acceleration estimate from one pass and using it as *a priori* for the next, suggest that longer single passes are equivalent to two consecutive shorter passes of the same length, but this is probably pessimistic.

This tracking scenario was simulated numerically, using spacecraft state and IPS thrust as the only estimated parameters, for a thrust uncertainty of 1 mN (corresponding to an acceleration uncertainty of 2×10^{-9} km/sec^2), both as a constant and as a stochastic parameter with a 1 hour update rate and a process noise scaled to match the constant uncertainty at 24 hours (*ie.* $\sqrt{24}$ mN). While the numerical results are still under development, the following results appear valid: 1) two passes are 100 times better than 1 pass for a constanc acceleration, 2) range data (versus Doppler-only) is 10 times better for 2 passes, but not much improvement for just one, and 3) stochastic accelerations at this level produce results that are 10 to 100 times worse than a single constant acceleration, and reduce the 2 pass benefit to merely a factor of 10.

The nominal DS1 thrust arc mode is to stop thrusting once per week for a HGA communications pass, a requirement imposed by spacecraft geometry if the optimal thrusting direction is to be maintained. From these numerical and analytic results, it is clear that avoiding continuous IPS thrusting while tracking is beneficial to orbit determination, even with the unbalanced RCS accelerations. While continuous thrusting during infrequent communication passes would be possible at the lowest thrust level without serious effects on the overall mission efficiency, doing so would require significantly more or different radio tracking to maintain reasonable orbit solution accuracy.

3 - CALIBRATION RESULTS

3.1 - IPS Acceptance Testing

The first use of the IPS in its full operational mode was planned as an acceptance test (IPS Acceptance Test 1 (IAT1)) to assess and measure engine performance. The IPS starting sequence pressurizes the engine to the maximum amount needed for any thrust level. Since the first desired thrust level (of about 20 mN) was nearly the lowest available, seven hours was allotted for the engine pressure to bleed down to a steady state level. Despite the expectation of somewhat unsteady thrust during this time, the plans for IAT1 included three spacecraft turns, to rotate DS1 by 30 degrees about its Y- and X-axis from the original attitude, defined by pointing the -Z axis at the Earth for maximum Doppler sensitivity during thrust calibration. The intent of this activity was to obtain a three-dimensional estimate of the thrust vector direction in spacecraft coordinates, although in retrospect this would have been difficult to obtain to a useful accuracy due to thrust level variations. Following the last turn (back to -Z to Earth), the IPS was to spend 1.5 hours at each of 6 increasing thrust levels (from 20 up to almost 80 mN), before being shut down either by command or autonomously as a result of overloading the solar array.

On November 10, 1998, IAT1 proceeded nominally through the various attitude control system modes leading up to the start of IPS thrust generation. However, after 4.5 minutes the IPS shut itself down due to the detection of a short across the accelerator grids. Continued efforts were made to restart the IPS during the remainder of the planned IAT1 sequence without success, and so IPS team analysis and testing begin to isolate and correct the problem. While this continued for two weeks, other aspects of the spacecraft operations were tested, including optical navigation image acquisition and (twice, inadvertently) spacecraft safe mode entry. Even though IAT1 only produced 12 mm/sec of IPS delta-V (along with a significant amount of RCS delta-V), the Doppler tracking data obtained by the DSN provided an exquisite measure of this result, due to the typical observed data noise frequently dropping to as low as 0.02 mm/sec (and never much worse than 0.05 mm/sec) for 10-second integration times over the first several months of the DS1 mission.

3.2 - IPS First Thrust Arc Results

The next attempt to start IPS thrusting came on November 24, 1998, as the continuation of a series of IPS diagnostic tests. To the general surprise of the DS1 flight team, the IPS came on and stayed on as commanded at the lowest thrust level, causing an immediate replanning effort to accomplish mission goals. The IPS thrust level was raised twice the following day before being lowered one level for the duration of the upcoming 4-day weekend (JPL Thanksgiving Day holidays). On November 30, 1998, four more higher thrust levels were exercised, and the IPS was left at the highest sustainable level to accumulate useful delta-V in accomplishing the asteroid encounter. The thrust attitude used for the first 10 days of IPS operation was not optimal for either trajectory change or IPS calibration, since the nominal attitude (spacecraft +X axis to Sun, with about 43 degrees from Earth to spacecraft -Z (the IPS exhaust direction)) was used to generate the IPS starting sequence without any strong expectation that IPS thrusting would continue so long at that attitude. However, the thrust direction was not unhelpful for obtaining useful delta-V, and the thrust component in the Earth direction was not seriously degraded, so useful results were obtained.

Due to the ongoing work of supporting current and future DS1 operations, the thrust levels of the first IPS thrust arc (IPS1) were not analyzed in detail until recently, and are first reported on here. The most interesting time spans are November 24-25 (IPS start through 3 thrust level changes) and November 30-December 1 (4 higher thrust levels and 7 thrust level changes). In addition to measuring IPS performance against predictions, the lower thrust levels provide a basis of comparison for IPS Acceptance Test 2 (IAT2), performed in May, 1999 after significant IPS usage, as described below. Short arc orbit solutions were obtained for each of these IPS1 timespans separately, using the methods described below.

To obtain accurate IPS thrust estimates over time, correct modelling of RCS thruster activity (especially in the spacecraft Z-axis, which is also the IPS thrust direction) and the time variability of the IPS thrust is essential. While the DS1 attitude control software accumulates an estimate of the RCS delta-V, known as the "nongrav history" file, the resulting data is not very useful for radio navigation due to the 10 mm/sec reporting threshold and 2 hour timeout rate. Instead, for this analysis spacecraft telemetry containing attitude estimates, RCS pulse counts, and RCS thrust on-times were processed to obtain attitude rate changes across each thruster firing event. Then, with a knowledge of the spacecraft moments of inertia and thruster moment arms, the RCS delta-V can be calculated to within a few percent in most cases, based on the Doppler residuals resulting from the use of the delta-V model. This approach does not work well when too many pulses are fired within a time too short to obtain a separate attitude rate on each pulse, so after the attitude-derived delta-Vs are added, additional impulsive delta-Vs are added as necessary based on Doppler residuals. Since the attitude rates and the antenna offset are big enough to produce noticeable Doppler residuals during deadbanding (but not IPS thrusting), the attitude rate estimates are used to approximately model and remove this effect.

IPS thrusting is modelled as a finite-burn manuever model that allows discrete thrust changes but does not allow the time of the thrust change to be estimated (except implicitly by allowing the manuever start time and duration to be estimated). Consequently, prefit adjustments of the time of each thrust change were performed, with the aid of a tool that estimated the time of a slope change in Doppler residuals without the thrust change modelled.[1] The thrust levels were also adjusted to obtain prefit Doppler residuals within a few mm/sec, so that the process noise assumptions in the estimation filter could be kept fairly small. Note that the IPS thrust modelling and the RCS delta-V modelling process are iterative, as impulsive delta-Vs only become apparent when the IPS thrust model is mostly complete. The IPS also has instances of thrust drop-outs due to momentary shorts (which are often confirmed by both Doppler residuals and telemetry). These are modelled as 0.2 to 0.3 mm/sec impulsive delta-Vs in the spacecraft -Z direction (cancelling part of the IPS +Z thrust).

Table 1: Standard Estimation Assumptions

Parameter	*A priori* σ	Parameter	*A priori* σ
Earth orientation:		Solar pressure	
Pole	30 nrad	Radial (Gr)	10%
UT1	50 nrad	Normal (Gx,Gy)	5% of radial
Troposphere:		Station locations	
Dry	1 cm	(fully correlated):	
Wet	4 cm	spin radius	8 to 9 cm
Ionosphere (X-band):		z-height	7 to 8 cm
Night	1.1 cm	longitude	5 to 6 cm
Day	5.6 cm	Range bias per pass	5 m

The estimation process uses a batch-sequential epoch state least-squares filter, with independent stochastic update times possible for each stochastic parameter. The standard estimation assumptions for all orbit solutions in this paper are given in Table 1, and the IPS1 assumptions are given in Table 2. Note that the solar pressure model is rather simple given the amount of other non-gravitational activity, and the relatively even dimensions of the spacecraft bus. The Doppler and range weights are tighter than would generally be considered reasonable for a longer arc, but the high level of quickly-changing model parameters makes weights close to the observed noise level acceptable. Constant spacecraft accelerations are used to account for remaining errors and biases in the RCS delta-V model that are not distinct enough to be modelled impulsively. The higher value of stochastic *a priori* σ (or process noise) was used for three 3 to 5 minute timespans right around the IPS start on November 24. The short IPS

[1] In the course of the current analysis, said tool was converted from Mk. 1 eyeball to Perl script.

thrust magnitude update rate, varying from 2 to 10 minutes depending on data noise and IPS stability, is set up to absorb most of the short period effects, since there isn't sufficient data content in the Doppler data to estimate thrust direction at the same time. The IPS thrust direction estimates are instead allowed to vary slowly and checked for general validity, with resulting changes to other parameters as necessary to enforce this result. Finally, the RCS delta-Vs are allowed to change in magnitude by 50 percent (1σ), to absorb errors in the RCS delta-V modelling process. It should be noted that there is a much higher degree of time-variability reflected in this model than that used in [Wolff 98] in analyzing IPS calibration performance, which points out the importance of obtaining actual flight data.

Table 2: IPS1 Estimation Assumptions

Estimated parameters		Data weights	
Parameter	*A priori* σ	Data type	Weight (1σ)
Impulsive mnvr. components Thrust start time	0.5 mm/s 1 sec	Doppler (60 sec) Range	0.03 mm/s 0.3 m
Estimated and Stochastic Parameters			
Parameter	Estimated *a priori* σ	Stochastic *a priori* σ	Update rate/ correl. time
S/c accelerations:			
X, Z-axis	5×10^{-12} km/s^2	10^{-11} km/s^2	1 hour/none
(short term)		10^{-9} km/s^2	1 min/none
Y-axis	10^{-12} km/s^2	5×10^{-12} km/s^2	6 hours/none
IPS thrust:			
magnitude	5 mN	2 mN	2 – 10 min/none
direction	2°	1°	1 hour/6 hours
RCS Δ-V scale	not estimated	50%	per Δ-V

Figure 2 shows the IPS thrust estimates and uncertainties from the first IPS1 arc, which includes data from 00:00 UTC on November 24, 1998 to 23:00 UTC on November 26, 1998. Note that the error corridors reflect only the stochastic estimate uncertainty, and that an additional 0.12 mN of error (1σ) in the absolute thrust level for the entire duration of thrusting is not shown. The main plot shows the IPS thrust level changes commanded on November 25 (from 21 mN to 32 and 47 mN before dropping back to 32 mN). The lower inset shows the first 16 hours at 21 mN (after the IPS started thrusting at about 22:53 UTC on November 24), and is notable for the thrust variation over the first 5 hours and the short period 0.2 mN variations over the last 12 hours. The short period variation may be due to estimation artifacts or data noise, but there is no clear evidence that this is an actual IPS effect. The upper inset shows 27 hours at 32 mN, and shows both short period noise and discrete changes at timescales of about an hour. The longer period changes in thrust level could be caused by 1-hour update rates in other stochastic parameters (in particular thrust direction), but that doesn't seem to be the case based on the thrust direction estimates. Periods without any tracking data show up as 1 mN error corridors, reflecting the *a priori* σ on the stochastic thrust estimates. The constant thrust direction uncertainty for this arc was about 0.5°, which is much better than would be expected from [Wolff 98], no doubt due to tracking through long periods of thrusting without any thrust level changes.

Figure 3 shows the IPS thrust estimates from the middle of the second IPS1 arc, which included data from 00:00 UTC on November 30, 1998 to 20:00 on December 1, 1998. The estimates from the first and last 16 hours of this arc (which are not shown on Figure 3) show IPS thrust levels at 32 and 72.5 mN remaining steady except for 0.2 mN of variation at a timescale of a few minutes (similar to the results from around 10:00 UTC on November 25 in

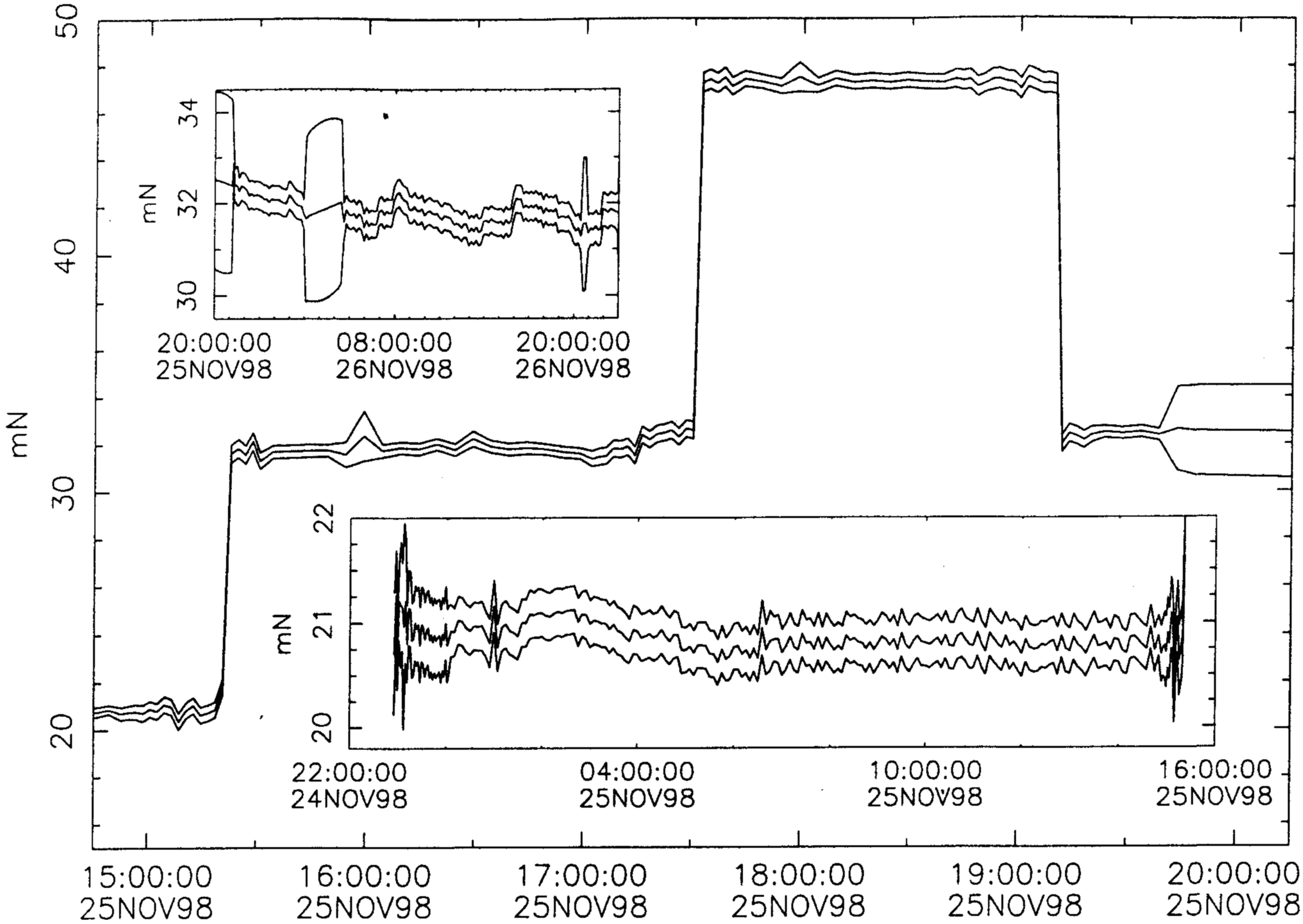

Fig. 2: IPS thrust estimates and 1 σ error corridor, November 24-26, 1998

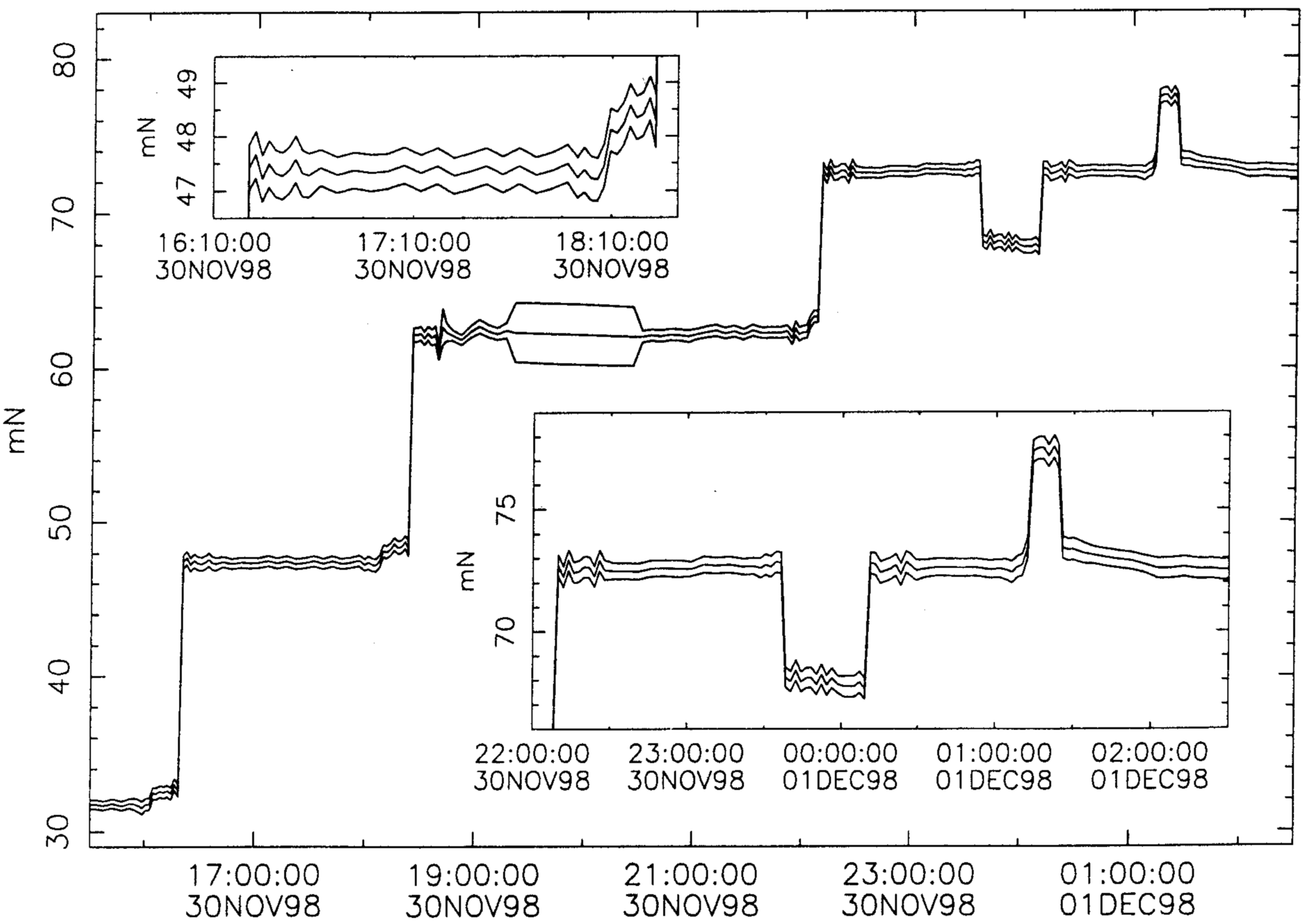

Fig. 3: IPS thrust estimates and 1 σ error corridor, November 30-December 1, 1998

Figure 2). The main plot shows IPS thrust changing from 32 mN to thrust levels of 48, 62, 68, 73, and 78 mN. The highest thrust level was only achieved for 12 minutes, since telemetry showed the battery draining at a significant rate. The estimated thrust levels are generally constant apart from transition periods, and a short interval around 18:30 UTC with significant RCS thruster activity. The transition periods show the effect of changes in the xenon flow rate on the thrust, even without current or voltage changes in the IPS. Every instance of increased thrust level is preceded by a pressurization to establish the new flow rate, which also increases the thrust by almost 1 mN. This can clearly seen in the upper inset, which details 48 mN operation at around 17:00 UTC. The lower inset shows the highest thrust levels in more detail. The effect of bleed down from a higher pressure is clear in the gradually declining thrust level at 68 mN and at 73 mN following the brief period of 78 mN operation. The constant thrust uncertainty for this arc is 0.406 mN, which is significantly higher than for the earlier IPS1 arc, probably due to the lack of any non-thrusting period within it. The thrust direction uncertainty is 0.6°, similar to the earlier arc.

3.3 - IPS Post Thrusting Results

IPS Acceptance Test 2 (IAT2) occurred on May 28, 1999, with a goal of evaluating IPS performance changes after a significant amount of use, which in this case amounted to nearly 1800 hours of IPS thrusting since launch. Since the geocentric range precluded any telemetry except on the high gain antenna (HGA), the first 5 hours were spent thrusting perpendicular to the Earth direction (a consequence of HGA mounting geometry) before turning the spacecraft -Z axis towards the Earth for maximum thrust observability. By the completion of the turn, the IPS pressures had reached steady-state levels, and a series of 5 thrust levels was exercised. Table 3 shows the IAT2 estimation assumptions, which are similar to those used for IPS1. The main differences were a tighter IPS thrust stochastic *a priori* σ, and the absence of a stochastic RCS delta-V scale factor. The Doppler data quality on the -Z LGA was not as good as for the earlier IPS1 arcs, even without telemetry, due to the increased range to the Earth.

Table 3: IAT2 Estimation Assumptions

Estimated parameters		Data weights	
Parameter	*A priori* σ	Data type	Weight (1σ)
Impulsive mnvr. components	Z-axis: 1.0 mm/s X,Y-axis: 0.5 mm/s	Doppler (60 sec) Range	0.1 mm/s 1.0 m
Thrust start time	1 sec		
Thrust duration	1 sec		
Estimated and Stochastic Parameters			
Parameter	Estimated *a priori* σ	Stochastic *a priori* σ	Update rate/ correl. time
S/c accelerations:			
Z-axis	10^{-10} km/s^2	10^{-11} km/s^2	1 hour/none
(Z, X briefly)		5×10^{-9} km/s^2	5 min/none
X, Y-axis	10^{-12} km/s^2	5×10^{-12} km/s^2	6 hours/none
IPS thrust:			
magnitude	5 mN	0.5 mN	$2-5$ min/none
direction	1°	0.5°	1 hour/2 hours

The IAT2 thrust estimates from the Earth-pointed period are shown in Figure 4. Due to increased flow requirements for low power levels, the xenon flow rate actually decreases from the 21 mN level in going to 24 and 27 mN, which may be the cause of the slight downward trend in the first hour of thrusting at 27 mN. Aside from the first thrust level, 31 mN is the only thrust level for which an exact comparison exists in IPS1, and unfortunately RCS activity (most likely brought about by IPS thrust dropouts, as described earlier) significantly disturbed the last half hour at this level. The final thrust level only lasted 25 minutes (as planned), due to concerns about battery discharge while operating at this power level. Thirty minutes after the sequenced IPS shutdown, the spacecraft started a turn back to the nominal HGA Earth-pointed attitude to return recorded telemetry from IAT2. The constant thrust uncertainty for IAT2 is 0.04 mN, which is probably so small due to the relatively short duration of the thrust and the Doppler and range data on each end of the thrusting. While the in-plane component of thrust direction is well determined at 0.12°, the normal component is not improved from the *a priori* uncertainty of 1°.

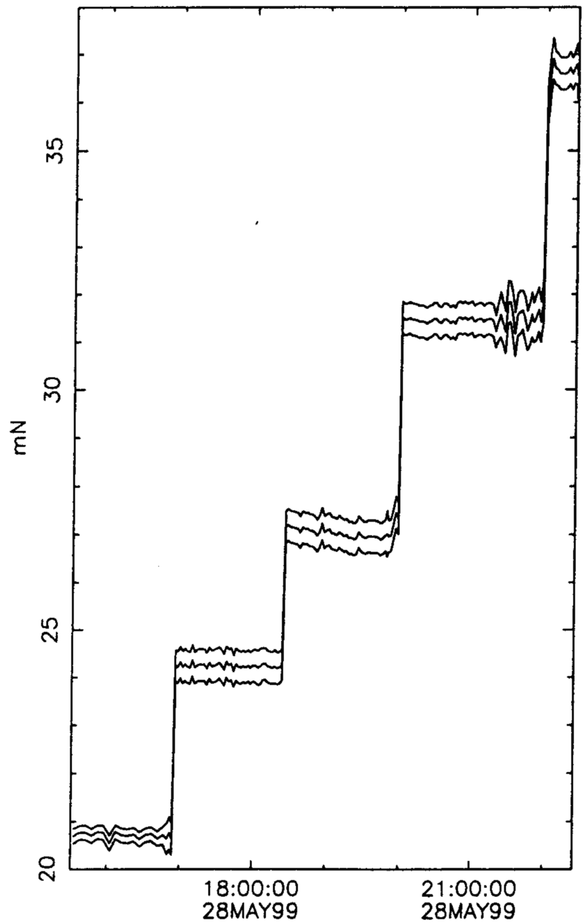

Figure 4: IAT1 thrust estimates and 1 σ error corridor

Table 4: IPS thrust estimates comparison

Nominal Thrust, mN	IPS1 thrust, mN (percent from nom.)	IAT2 thrust, mN (percent from nom.)
20.7 (# 6)	20.797 ± 0.125 ($+0.49 \pm 0.60$)	20.705 ± 0.082 ($+0.05 \pm 0.40$)
24.6 (# 13)		24.234 ± 0.065 (-1.29 ± 0.26)
27.5 (# 20)		26.985 ± 0.073 (-1.75 ± 0.27)
32.1 (# 27)	31.766 ± 0.214 (-1.10 ± 0.67)	31.460 ± 0.074 (-2.05 ± 0.23)
37.4 (# 34)		36.616 ± 0.231 (-1.98 ± 0.62)
47.9 (# 48)	47.298 ± 0.140 (-1.19 ± 0.29)	
63.2 (# 69)	62.227 ± 0.412 (-1.49 ± 0.65)	
73.6 (# 83)	72.561 ± 0.408 (-1.41 ± 0.55)	
78.4 (# 90)	77.388 ± 0.449 (-1.27 ± 0.57)	

3.4 - IPS Thrust Level Comparisons

Since the total thrust estimate changes frequently with the stochastic update rates used in these solutions, average thrust levels for comparison purposes are obtained by statistically combining the thrust estimates over representative timespans and the constant thrust estimate over the entire arc. In addition to the formal uncertainty, the standard deviation of the individual estimates is computed, and whichever value is larger is adopted as the reported uncertainty. Consequently, the averaging time span is chosen to minimize the variability in the estimated thrust, even at some cost in formal uncertainty.

The average thrust levels from IPS1 and IAT2 are shown in Table 4, along with the nominal thrust (followed in the same cell by the thrust level number from a range of 112 possible values). The constant thrust level uncertainty from the November 30-December 1 arc of IPS1 is 0.4 mN, probably due to the lack of a non-thrusting part of the data arc and resulting correlations between thrust magnitude and direction, so IPS1 values from November 25 are used up through 48 mN. The percentage difference from nominal is given for each average thrust. While the lowest thrust shows a half percent increase from nominal, all other thrust levels are 1.1 to 1.5 percent low. The IAT2 results show a consistent further 0.5 to 1.0 percent degradation, although there are only two common thrust levels. These results suggest that future IPS use on longer missions should allow for at least a one-percent degradation. Since a further 6000 hours of IPS use are planned for DS1, performance tests at the end of IPS use or thrust levels derived during IPS use may be able to bound or at least measure any further changes in IPS thrust levels.

4 - ORBIT DETERMINATION RESULTS

4.1 - Orbit Determination Method and Results

The DS1 thrust arc of March 16 to April 27, 1999 was broken into roughly one-week segments, with an Autonav optical navigation (opnav) image acquisition and processing session and HGA communications pass following each thrusting period. Radio tracking data was limited to Doppler and ranging during the 10 hour HGA pass and several LGA Doppler-only tracks of about 4 hours during IPS thrusting. The IPS start was scheduled such that the first thrusting on each segment was visible in the Doppler data at the end of the tracking pass.

The nominal thrust model included discrete changes in thrust (due to changing power availability as a result of solar distance changes) and direction, the latter at roughly twelve-hour increments to approximate a linear profile throughout each segment. In practice, autonomous battery management algorithms and ground commands changed the thrust level many more times than the 1 to 2 changes that would be typical due to power changes. Consequently, the recorded data returned from each HGA pass and the command history were required before the weekly orbit solution could be obtained. The "nongrav history" file was also used to construct a delta-V model for each opnav session, consisting of a impulsive delta-V at the beginning and end of each opnav to match the total velocity and position change reported for that interval.

The estimation approach was generally similar to that reported for IPS1 and IAT2 above. The update rate for thrust changes was often much longer due to the lack of continuous tracking, and the impulsive delta-V *a priori* uncertainties were much larger, since each opnav session produced a delta-V of up to 100 mm/sec (mostly from the tight opnav pointing deadbands being maintained by the unbalanced RCS Z thrusters). The few occasions when tracking data was collected for the first few hours of IPS thrusting were used to construct an approximate model for use without visibility, and the sequenced, commanded, and autonomous IPS thrust level changes were included in the thrust model. Even with the significant amount of effort required to obtain orbit solutions extending through the last HGA pass, precise prediction to the next target (asteroid Braille) was impossible due to the unplanned thrust changes that invariably occurred. However, reasonable orbit determination accuracy was maintained within the data arc, and periodic replaning of the trajectory (both onboard and ground-based) succeeded in obtaining an adequate trajectory by the end of April, 1999.

Low-thrust missions can typically accomodate trajectory correction delta-Vs of several meters per second with almost no impact on to the total delta-V budget, and any final pre-target thrust arc that ends with remaining errors of this magnitude is a success, as long as there is enough coast time before the encounter to make the corrections with the low-thrust system. For DS1's encounter with Braille, 3 months were allowed from the end of the thrust arc to encounter, which was enough time to accomplish both other mission objectives and IPS trajectory correction maneuvers, some of which were scheduled to last as long as 24 hours. By contrast, future missions planning a short coast arc before an encounter need to be studied in more detail to make sure that the thrust predictability and orbit determination requirements are consistent with a short encounter timeline.

4.2 - Orbit Determination Consistency

As mentioned in Section 2 above, DS1 orbit determination benefited from having at least one tracking pass per week with the IPS off, and relatively low LOS acceleration errors from RCS activity. The HGA pass was also often split between two stations, which was quite helpful for determining geocentric declination, particularly in the several cases where the two stations were in the Goldstone and Canberra complexes. Every orbit solution produced a state covariance at the end of the data arc, so the associated state estimate can be compared to solutions from following weeks, where the comparison epoch is within the data arc and presumably better determined. Each solution's propagation through the following week can be compared with a later reconstruction as well, with an assumed position uncertainty of 150 km based on 1 percent thrust magnitude and 10 mrad thrust direction errors. Figure 5 shows that the covariance and the errors were consistent within the data arc, but that a one-week prediction had errors of over 450 km, mostly due to the unpredicted thrust level changes.

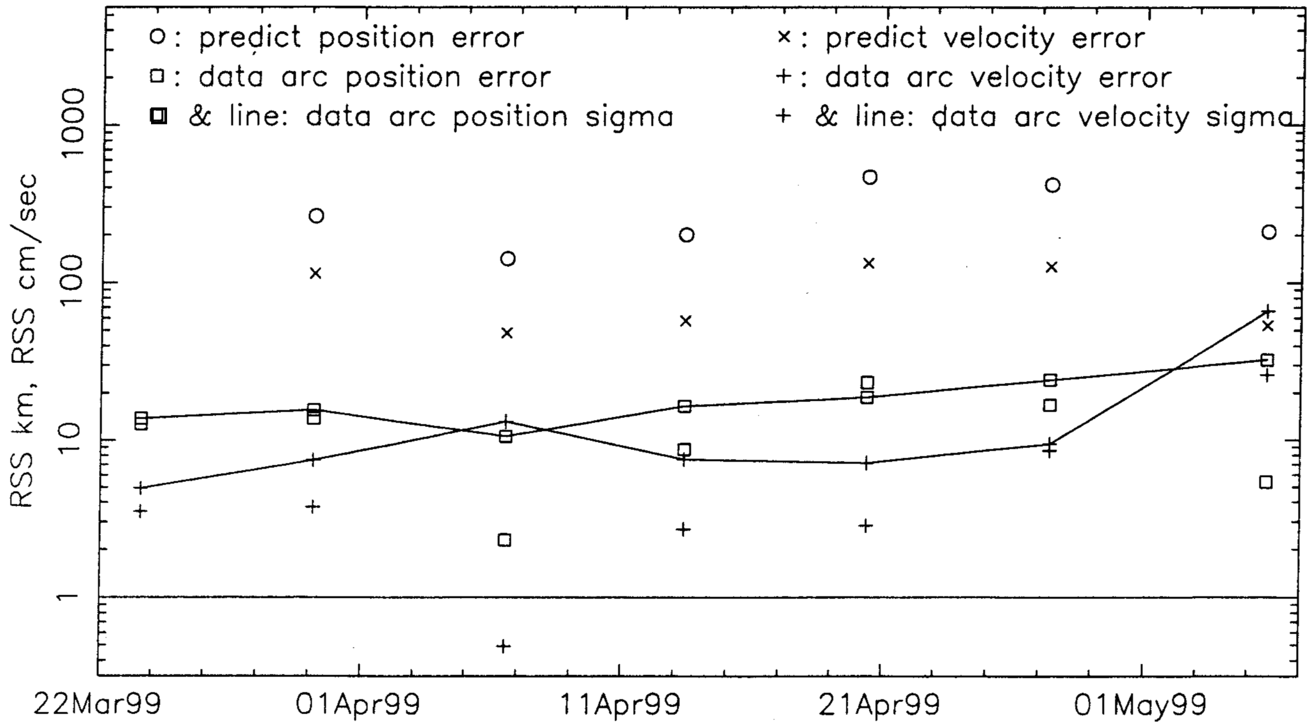

Figure 5: Orbit solution consistency within the data arc and with one week's prediction

5 - CONCLUSIONS

DS1 was a difficult spacecraft to navigate with radio tracking data, but careful modelling of spacecraft accelerations allowed adequate results to be obtained in meeting technology goals and enabling the asteroid encounter. In examining the challenge presented by large acceleration errors, the navigational insensitivity of Doppler and range tracking data from a single pass is highlighted, suggesting that the recent trend toward short, infrequent passes is often unwise. Consecutive tracking from two stations is shown to ameliorate this problem, and obviously interferometric tracking strategies, from alternate hemisphere ranging to VLBI, completely restore angular knowledge. The navigation experience with the IPS system suggests that a large predicted thrust level uncertainty must be accommodated in mission plans, although for long thrust arcs there is ample time to continuously correct errors. IPS performance changes to date suggest that thrust degradation should be allowed for, although as has been pointed out often recently, the practice of designing spacecraft with unbalanced thrusters and without momentum wheels (such as DS1) makes radio navigation difficult.

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